

# RESEARCH MEMORANDUM

EFFECT OF IMMERSED SURFACES IN COMBUSTION ZONE ON

EFFICIENCY AND STABILITY OF 5-INCH-DIAMETER

RAM-JET COMBUSTOR

By Thaine W. Reynolds and Donald W. Male

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# NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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#### SUMMARY

An extension of previous work on immersed surfaces in the combustion zone of a ram-jet engine is reported. It is shown that when a single blade is mounted perpendicular to and downstream of a V-gutter flame holder in a 5-inch-diameter ram jet, the performance of the ram jet is markedly affected by the axial position of the blade. At an inlet pressure of 1 atmosphere, an inlet velocity of 220 feet per second, an inlet temperature of 660° R, and an equivalence ratio of 1.0, it is possible to increase the combustion efficiency of the ram jet from 60 percent to 80 percent by proper location of the blade. However, the stability of the system without auxiliary piloting is poorer with the blade present. The higher combustion efficiency is obtained with considerably less pressure drop than was encountered in a previous investigation with a multiple-blade arrangement that gave high efficiencies. A small amount of continuous pilot heat can effect large improvements in stability limits.

#### INTRODUCTION

One of the basic advantages attributed to the ram-jet combustor is its mechanical simplicity. However, a certain amount of hardware must be incorporated in the combustor in order to stabilize a flame and have it propagate through the high-velocity combustible mixtures flowing through the ram jet.

The basic types of flame holders currently found to be suitable are the can and simple baffle, such as the V-gutter. The can flame holder provides a greater control of the combustion progress through the engine, but usually has a larger pressure drop and more complicated construction than the simple baffle-type flame holders. The baffle

flame holder, while permitting a comparable stability regime with less pressure drop, maintains essentially no control over the subsequent mixing and flame-spreading process beyond its normal wake region.

The use of flame-immersed surfaces offers a means of retaining the mechanical simplicity and low pressure losses of the gutter flame-holder system while achieving some measure of control of the mixing in the combustion zone. Reducing the pressure losses of the combustor with flame-immersed surfaces below those of reference l would be particularly advantageous in an afterburner application, for example, since the additional drag accompanying the added immersed surface during nonburning operation would be relatively small.

It was shown in reference 1 that the introduction of immersed surfaces in the combustion zone downstream of a single V-gutter flame holder improved both the combustion efficiency and stability over those obtained with the gutter alone. The improvement in efficiency was obtained through increased mixing of hot combustion products with incoming combustible mixture, since the effects of temperature of the surfaces was of secondary importance. The blades used in the investigation of reference 1 were placed so that they would not interfere with the normal recirculation zone of the V-gutter. However, the increased efficiencies were obtained at the expense of somewhat larger pressure drops than those obtained with the gutter alone.

The present investigation was undertaken to determine the effect on combustion efficiency and stability of blades located within the immediate wake of a V-gutter flame holder and, if possible, to find some location and orientation of blades for optimum combustion efficiency and improved stability limits with a minimum of pressure loss.

The experimental work was performed with a 5-inch-diameter connected-pipe ram jet at the NACA Lewis laboratory.

#### APPARATUS

The connected-pipe setup used in this investigation is shown schematically in figure 1. Electrically preheated and metered air at 40 pounds per square inch gage pressure was supplied to the inlet of the tank containing the air-control unit. Air mass flow was controlled by maintaining choked flow through the air-control unit shown in the insert of figure 1 and exposing a sufficient number of holes in the sliding plates to obtain the desired mass flow. Fuel was introduced through an air-atomizing spray bar at the diffuser inlet.

The fuel-air mixture passed through the 10-foot-long diffuser, where sufficient time was available for vaporizing and mixing, and was

ignited by a hydrogen-oxygen pilot flame located behind the flame holder. The flame holder was a  $1\frac{1}{2}$ - by  $1\frac{1}{2}$ -inch V-gutter extending across a diameter and blocking about 38 percent of the combustor cross-sectional area. The combustion chamber, a 5-inch-diameter water-cooled pipe section, was 36 inches long. Two different burner spool sections were used, as shown in figure 2(a) and (b). The blades, which were 13/16-by  $3\frac{1}{2}$ - by 1/8-inches, were made of molybdenum coated with molybdenum disilicide and were cantilever-mounted in the combustor through pipe fittings. The various configurations investigated are indicated in figure 2(c). The static-pressure drop was measured by a mercury manometer connected from the inlet pressure tap in the combustor wall upstream of the flame holder to the similar downstream tap at the exhaust end of the combustion chamber.

A variable-area exhaust nozzle controlled the burner-inlet pressure. In order to cool the combustion products to 1060°R and quench the reaction, water was introduced through two air-atomizing spray bars just downstream of the exhaust nozzle. The equilibrium exhaust-gas temperatures were measured by an array of thermocouples located about 15 feet farther downstream. The combustion efficiency was then calculated by an enthalpy balance.

# PROCEDURE AND CALCULATION

The procedure used in obtaining the test data was as follows: The air mass flow and temperature were set at a predetermined value. The burner was ignited and the fuel flow set at some value in the stable burning regime. The pilot was turned off before recording data. The inlet pressure was then set at the desired operating point by adjusting the variable-area exhaust nozzle. The quench-water flow rate was set so that the exhaust-gas temperature was maintained at about 1060° R.

The combustion efficiency was then calculated by the following equation:

$$\eta = \frac{\Delta H_{W} + \Delta H_{\Theta} + \Delta H_{j}}{(H_{C})(f/a)}$$
 (1)

where

n combustion efficiency

 $\Delta H_{W}$  enthalpy rise of water used to quench exhaust gases, Btu/lb original air

ΔHo enthalpy rise of exhaust gases, Btu/lb original air

ΔH; enthalpy rise of cooling jacket water, Btu/lb original air

H<sub>c</sub> lower heat of combustion of fuel, Btu/lb

f/a weight fuel-air ratio

and where for mixtures richer than stoichiometric,

$$\Delta H_{e} = \Delta H_{s} + \left[ \left( f/a \right)_{e} - \left( f/a \right)_{s} \right] \left[ \left( L_{v} \right)_{T_{i}} + C_{p} \left( T_{e} - T_{i} \right) \right]$$
 (2)

whe :

ΔH<sub>s</sub> enthalpy rise of stoichiometric mixture, Btu/lb original air

(f/a) actual weight fuel-air ratio

(f/a) stoichiometric weight fuel-air ratio

Lv latent heat of vaporization of fuel, Btu/lb

Ti inlet mixture temperature, OR

Cp mean heat capacity of fuel, Btu/lb, value of 0.5 assumed for this report

Te temperature of exhaust gas, OR

In this method of determining combustion efficiency, where the reaction products are cooled rapidly to a low temperature, the composition of the exhaust gas is probably frozen at its equilibrium composition at the combustor exit. In this case, the measurable amount of sensible heat in the exhaust gas is less than the net heating value of the fuel by the amount tied up in the dissociated products. This dissociation enthalpy may amount to about 7 percent of the lower heating value at stoichiometric conditions (ref. 2). The combustion efficiencies reported herein include no correction for this effect.

The procedure used in obtaining the stability limits was to set the burner operating in the stable range with the pilot off as mentioned before, and then to reduce fuel flow slowly while maintaining the burner-inlet pressure constant until the burner went out. In the cases where piloting was maintained, the stability limits reported are not blow-out limits but merely the limits of stable burning. Without piloting, there was no region of unstable burning, and the stability limits reported

are blow-out limits. The minimum pressure points were obtained by holding the fuel flow constant and slowly lowering the burner-inlet pressure until the flame blew out or the nozzle was wide open and a choking condition existed.

The combustion efficiency and stability limits were determined for the following series of configurations shown in figure 2(c): (1) a single blade mounted perpendicular to the V-gutter at several axial positions, (2) a single blade parallel to the V-gutter at several axial positions, (3) a single blade perpendicular to the V-gutter at several axial positions and blade angles, and (4) a four-blade arrangement consisting of one perpendicular blade at the 1-inch position and three parallel blades at the  $2\frac{1}{2}$ -, 4-, or  $5\frac{1}{2}$ -inch positions.

## RESULTS AND DISCUSSION

The data obtained in this investigation and discussed herein are presented in table I.

The results of the combustion-efficiency measurements on the series of single perpendicular blade arrangements at inlet pressure of 1 atmosphere, temperature of 660° R, and inlet velocity of 220 feet per second are shown in figure 3, where combustion efficiency is plotted against equivalence ratio for several axial positions of the blade. The ends of these curves do not necessarily mean blow-out was reached. In some instances, only the combustion efficiency near stoichiometric was of interest, and the complete equivalence-ratio range was not investigated. It will be noted that two different burner spools were used, and the combustion efficiency of the V-gutter alone was about 4 percent higher for spool II than for spool I. The greater number of openings in spool II apparently created more flow disturbances than the relatively smooth surface of spool I and thereby caused the slightly higher combustion efficiencies. In subsequent figures, however, the efficiencies obtained with either spool are plotted as determined.

A cross plot of the combustion efficiency at an equivalence ratio of 1.0 against axial location of the blade is given in figure 4. This curve shows the marked effect of blade positioning on the combustion efficiency. An increase of nearly 20 percentage points in combustion efficiency was obtained for the blade located  $2\frac{1}{2}$  inches from the gutter over the combustion efficiency of the V-gutter alone. Approaching too close to the flame holder apparently disturbs the normal wake region and can cause deleterious effects on the performance, since a slight drop in combustion efficiency was noted at the 1-inch blade position.

Although the blades were not cooled, they never reached temperatures much above about 2000° R. Thus, though the blade may be serving as a sink for heat or active particles, it is apparently also providing an intensive mixing zone downstream and is promoting greater flame spreading.

The blade close to the gutter also strongly affected the stability limits. Figure 5 shows the fuel-air-ratio limits of stable operation as a function of the inlet pressure for several of the same configurations as shown in figure 4. The inside of the loop represents the operable region; and the outside, the nonoperable region. The V-gutter alone had the widest operable fuel-air-ratio range for a given pressure and the lowest operable pressure. As a blade was inserted and moved toward the flame holder, the operating range was decreased markedly. The operating range may be quite narrow at an inlet pressure of 1 atmosphere with the blade positioned closer to the gutter than 4 inches. This was indeed the case, and on some occasions no operation could be obtained with the blade close to the gutter without auxiliary piloting. This sensitivity was undoubtedly a result of variation in the steadiness of the air supply from one day to another. Comparative plots, however, were all taken during a single operating period whenever possible, so that consistency in the comparisons is maintained.

Reference 1 showed that twelve blades positioned for mixing increased the combustion efficiency over that of the V-gutter alone by about 20 percentage points at an inlet pressure of 1 atmosphere, an inlet velocity of 220 feet per second, an inlet temperature of 660° R, and an equivalence ratio of 1.0. The results of the present investigation show that a single blade, properly located, can increase the combustion efficiency by the same amount, and at the same time introduce a pressure drop across the burner which is considerably less than that incurred by the multiple-blade arrangement of reference 1. However, this result is achieved with a smaller stability range than was obtained with the V-gutter, while the multiple-blade arrangement had a greater stability range than was obtained with the V-gutter alone. Figure 6 shows a comparison of the static-pressure drop of the single-blade configuration and the 12-blade configuration (table II), along with the theoretical pressure losses resulting from heat addition in a constant-area duct with two different values of friction pressure loss upstream of the region of heat addition. These friction pressure losses are expressed in terms of  $\Delta p/q$  or the ratio of total-pressure drop to inlet dynamic head. The pressure drop for comparable efficiencies was considerably less for the single-blade configuration. The effect that pressure drops of this order of magnitude would have on the specific fuel consumption of an engine will depend upon the flight conditions the engine will encounter. Analysis for an afterburner case indicated that a change in flame-holder friction pressure loss Ap/q from 1 to 3 can be equivalent to losses in combustion efficiency of 6 percent and greater.

Since reference I also showed that considerable improvement in stability limits could be obtained with multiple blades placed parallel to the V-gutter, it was desirable to investigate the possibility of using a single parallel blade to produce this same effect also. Figure 7 shows the pressure against equivalence-ratio curve for the V-gutter alone and for three axial positions of a parallel-mounted blade. It is seen that no effect on stability limits resulted from these variations. Although the data are not presented herein, there was no effect for these variations on combustion efficiency, either.

The effect of varying the angle of attack of the blades mounted perpendicular to the V-gutter was also investigated. The angle of attack is here defined as the smallest angle between the axis of the burner and the flat side of the blade (fig. 2(c)). Figure 8 shows the effect of varying the blade angle on combustion efficiency for several blade positions, and figure 9 shows the effect of the blade angle on stability limits for the blade mounted at  $2\frac{1}{2}$  inches. As the blade intercepts more of the stream, up to an angle of about  $30^{\circ}$ , the combustion efficiency is increased. Beyond this angle any further effect is slight. Similarly, as the blade angle is increased, the stability limits are decreased. The limits and efficiency level-off at about the same positioning of the blade.

Since it was shown that one blade, properly located perpendicular to the axis of the V-gutter, could markedly increase the combustion efficiency, and since it has been shown in reference 1 that several blades oriented parallel to the V-gutter increase the stability, it was thought that some combination of parallel and perpendicular blading might improve both the efficiency and stability without prohibitively increasing the pressure drop. Obviously, a large number of variations is possible, and only comparatively few were investigated. In figure 10 the combustion efficiencies of two configurations are compared with that of the V-gutter alone. A combination of one perpendicular blade at the 1-inch position and three parallel blades at the  $2\frac{1}{2}$ -, 4-, and  $5\frac{1}{2}$ -inch positions (fig. 2(c)) had a combustion efficiency about 16 percentage points higher than that attained with the V-gutter alone at an inlet pressure of 1 atmosphere, an inlet velocity of 220 feet per second, an inlet temperature of 660° R, and an equivalence ratio of 1.0. At the same conditions, a single blade at the 4-inch position had a combustion efficiency about 18 percentage points higher than that attained with the V-gutter. A comparison of the stability limits of these same configurations (fig. 11) shows that the configuration with four blades, while not as stable as the V-gutter alone, has improved limits over the single-blade configuration.

Pressure fluctuations imposed upon a burner may be either attenuated or amplified, according to reference 3. The tendency to amplify pressure fluctuations (and, therefore, probably to decrease stability) increased

with temperature ratio across the burner and with lower-pressure-loss flame holders. This amplification tendency may be the reason that the high-efficiency, low-pressure-loss single-blade configuration is less stable than the V-gutter, while the high-pressure-loss multiple-blade configuration is more stable than the V-gutter.

The stability limits reported herein have all been with no auxiliary piloting. The stability limits may be improved considerably by maintaining a small amount of piloting in the sheltered zone (table III). Figure 12, for example, shows the marked improvement in stability possible with pilot heats equal to 0.7 and 1 percent of the net heating value of the stoichiometric fuel-flow rate with the V-gutter alone and with the gutter plus one perpendicular blade at the  $5\frac{1}{2}$ -inch position. The stability curves shown for the piloted case are not blow-out limits but merely rough-burning limits, while the nonpiloted curves are blow-out limits. The V-gutter with only 0.7-percent pilot heat operated stably at choking conditions and 0.3 atmosphere, whereas the minimum operable pressure without pilot was about 0.46 atmosphere.

An increase in pilot heat to 1 percent widened the smooth-burning range considerably. A similar increase in the stable-burning range was noted for the gutter-plus-blade configuration (fig. 12(b)), where without pilot the lowest operable pressure was about 0.67 atmosphere, and with 0.7-percent pilot the burner was still operating smoothly at a choked condition at 0.57 atmosphere.

The results reported herein were all taken with cooled combustor walls and with blades that, while not internally cooled, never got much above about 2000° R, since they were mounted in the cooled spool section and lost heat by conduction. It is possible that the stability and efficiency effects of these blades might be altered if the surfaces were allowed to approach flame temperature.

### SUMMARY OF RESULTS

The following results were obtained in a 5-inch-diameter ram-jet combustor with various arrangements of flame-immersed surfaces:

- 1. A single blade mounted perpendicular to and downstream of the V-gutter had a marked effect on the stability and efficiency of the burner, depending on its axial location.
- 2. The same increase in combustion efficiency was obtained with a single blade as had been obtained previously with a multiple-blade configuration, with a resulting considerably smaller pressure loss.

3. The highest combustion efficiency with a single flame-immersed blade was obtained with the blade at a position  $2\frac{1}{2}$  inches from the gutter. With this configuration, the combustion efficiency was about 80 percent; whereas the combustion efficiency was about 60 percent without the flame-immersed blade.

- 4. As a single blade mounted perpendicular to the flame holder approached the flame holder, the stability limits without auxiliary piloting became poorer.
- 5. A single blade mounted parallel to the V-gutter had no effect on the stability limits or efficiency at any of the locations investigated.
- 6. A small amount of continuous pilot heat effected large improvements in stability limits.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, March 22, 1954

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- 3. Dangle, E. E., Cervenka, A. J., and Perchonok, Eugene: Effect of Mechanically Induced Sinusoidal Air-Flow Oscillations on Operation of a Ram-Jet Engine. NACA RM E54DOl, 1954.

TABLE I. - SUMMARY OF PERFORMANCE DATA

Air flow, lb/sec	Inlet static pressure, atm	Inlet mixture temper- ature, OR	Inlet velocity, ft/sec		Combustor efficiency, percent	Blow- out	Static- pressure drop, $\triangle p$ , in. Hg
		V-Gi	itter; no	blade;	spool I		
1.820 1.825 1.825 1.825 1.830	1.0	652 646 643 638 636	214 213 212 210 210	0.902 .963 1.024 1.092 1.152	59.3 60.1 59.9 57.9 55.0		5.05 5.4 5.8 6.15 6.35
1.825 1.825 1.825 1.825 1.830		632 628 628 649 650	208 207 207 214 214	1.220 1.286 1.350 .900 .836	51.5 47.0 60.0 59.8	Rich	6.45 6.45 5.1 4.65
1.830 1.580 1.585 1.310 1.320		650 661 635 659 638	214 226 218 234 228	.777 .804 1.330 .846 1.272		Lean Rich Lean Rich	
1.320 .985 .980 .870	.500 .500 .45	639 653 644 647 647	228 232 228 226 225	1.257 .960 1.152 1.092 1.096		Rich Lean Rich Press	3.
1.27 1.30 .96 .90	.67 .67 .50 .50	661 643 653 643 657	227 225 225 209 231	.873 1.251 1.004 1.190 .962		Lean Rich Lean Rich Lean	
.90 1.06 1.06 1.55 1.56	.46 .58 .58 .83	652 664 648 674 646	229 218 211 226 218	1.058 .896 1.240 .820 1.324		Press Lean Rich Lean Rich	<b>a</b>
1.82 1.82 b1.78 b1.80 b1.80	1.01 1.0 1.0 1.0	672 644 656 658 651	220 213 211 214 211	.778 1.354 1.049 .956 1.128	63.3	Lean Rich	6.85 6.25 7.25

aMinimum pressure.

bSpool II.

TABLE I. - Continued. SUMMARY OF PERFORMANCE DATA

Air flow, lb/sec	Inlet static pressure, atm	Inlet mixture temper- ature, OR	Inlet velocity, ft/sec		Combustor efficiency, percent	Blow- out	Static- pressure drop,	Angle of attack, deg
1	J-Gutter an	nd one pe	erpendicula	ar blade	e at 1-in. po	sition	; spool I	
1.810 1.840 1.820 1.820 1.820	1.0	652 650 651 651 650	213 216 214 214 214	1.034 .956 .902 .836 .922	75.0 78.0 79.5 78.9	Lean	9.85 9.45 8.65 8.85	
1.830 1.825 1.825 1.825 1.825		646 642 638 651 650	213 211 210 214 214	1.023 1.092 1.155 1.210 .900	76.4 73.2 69.0 78.2	Rich	10.0 10.4 10.50 8.65	
1.825 1.825 1.80 1.80 1.80		650 646 656 657 657	214 212 214 214 212	.858 .984 1.036 1.036 1.042	77.9 77.5 64.4 73.1 76.6		8.1 9.55 6.60 8.3 9.1	0 15 30
V-	-Gutter and	d one per	rpendicular	r blade	at 2.5-in. p	osition	n; spool ]	
1.735 1.800 1.800 1.800 1.800	1.0	683 661 656 652 648	214 215 213 212 210	0.946 .912 .977 1.040 1.107	81.3 80.1 79.6 77.5 73.6		8.1 8.55 9.1 9.65 10.05	
1.800 1.810 1.810 1.84 1.82		648 657 657 653 653	210 214 214 215 214	1.148 .908 .908 1.02	80.1 84.6 84.1	Rich Lean	11.6	90
1.82 1.81 1.81 1.82 1.82		654 654 653 652 653 654	215 214 213 214 214 215	1.028 1.034 1.034 1.028 1.030 1.028	83.9 84.2 83.3 83.3 80.5 73.5		11.30 11.10 10.95 10.65 9.8 8.25	75 60 45 30 15

TABLE I. - Continued. SUMMARY OF PERFORMANCE DATA

Air flow, lb/sec	Inlet static pressure, atm	Inlet mixture temper- ature, OR	Inlet velocity, ft/sec		Combustor efficiency, percent	Blow- out	Static- pressure drop,	Angle of attack, deg
	V-Gutter a	and one p	perpendicu	lar blad	le at 4-in. p	osition	n; spool	I
1.74 1.73 1.73 1.74 1.73	1.02	671 670 666 662 660	206 209 208 207 206	0.946 .950 1.017 1.078 1.152	78.3 78.6 77.4 74.2 68.8		7.5 7.55 8.00 8.3 8.45	
1.73 1.73 1.73 1.73		660 674 675 678 678	206 210 210 211 211	1.173 .951 .886 .843	78.4 81.6 81.3	Rich	7.55 7.0 6.55	
1.78 1.80 1.79 1.54 1.54	.83	663 649 663 659 658	212 211 214 220 219	.840 1.128 .855 .963 1.017		Lean Rich Lean Pressa Pressa	3_	
1.67 1.67 1.82 1.82	.90 .90 1.0	667 660 654 644 644	223 221 214 211 210	.885 1.053 1.03 1.03 1.034	60.2 72.8 75.0	Lean Rich	5.9 8.2 8.65	0 30 45
1.80 1.82 1.82 1.80 1.81		645 644 648 646 666	210 212 212 210 217	1.036 1.024 1.030 1.036 .789	76.1 69.0 62.2	Lean	8.9 9.1 7.3 5.95	60 75 15 0 45
1.80 1.80 1.80 1.80		645 678 652 676 657	210 220 211 219 213	1.227 .771 1.316 .808 1.218		Rich Lean Rich Lean Rich		45 0 0 30 30
1.80 1.80 1.80 1.80	.83	675 675 661 662 680	218 218 214 214 226	.831 .843 1.131 1.112 .790		Lean Rich Rich Lean		60 60 60 60

a<sub>Minimum</sub> pressure.

TABLE I. - Continued. SUMMARY OF PERFORMANCE DATA

Air flow, lb/sec	Inlet static pressure, atm	Inlet mixture temper- ature, OR	Inlet velocity, ft/sec		Combustor efficiency, percent	Blow- out	Static- pressure drop,	Angle of attack, deg
	V-Gutter	and one p	perpendicu	lar blad	de at 4-in. p	position	n; spool	1
1.54 1.53 1.53 1.53 1.53	0.83	656 685 669 683 673	218 227 222 226 222	1.298 .825 1.158 .864 1.095		Rich Lean Rich Lean Rich		0 30 30 60 60
1.28 1.28 1.28 1.40 1.40	.67 .67 .67 .75	682 663 673 671 659	235 230 227 226 223	.846 1.238 1.022 .88 1.095		Lean Rich Pressa Lean Rich		0 0 30 30 30
1.54 .93 1.08 1.09	.85 .52 .58	670 657 668 657	220 213 224 221	957 1.138 .918 1.200		Pressa Pressa Lean Rich		60 0 0
V	-Gutter and	nd one pe	erpendicula	ar blade	at 5.5-in.	positio	n; spool	I
1.76 1.76 1.75 1.74 1.74	1.0	646 646 644 642 640	205 204 203 202 202	0.933 1.002 1.070 1.144 1.208	75.8 74.9 72.4 67.3 61.7		7.2 7.5 7.8 7.9 7.9	
1.74 1.74 1.74 1.75 1.75		640 658 661 670 670	202 206 207 211 211	1.252 .944 .879 .814 .783	76.5 78.4 75.4	Rich	7.1 6.5 5.9	
1.79 1.79 1.55 1.55 1.54	1.01 1.0 .84 .83	674 652 671 656 657	216 211 224 220 219	.801 1.221 .825 1.158 1.161		Lean Rich Lean Rich Rich		
1.54 1.26 1.26 1.28 1.18	.83 .67 .67 .67	676 674 664 663 660	225 229 227 229 228	.825 .900 1.050 1.035 1.017		Lean Lean Rich Rich Pressa		,

<sup>&</sup>lt;sup>a</sup>Minimum pressure.

TABLE I. - Continued. SUMMARY OF PERFORMANCE DATA

Air flow, lb/sec	Inlet static pressure, atm	Inlet mixture temper- ature, OR	Inlet velocity, ft/sec		Combustor efficiency, percent	Blow- out	Static- pressure drop,  ^pp, in. Hg	Angle of attack, deg
7	-Gutter and	nd one pe	erpendicul	ar blade	e at 5.5-in.	positio	on; spool	I
1.18 1.12 1.82 1.83 1.82	0.63 .61 1.0	663 655 654 651 650	222 219 214 215 214 213	0.926 1.004 1.028 1.023 1.024	63.5 72.0 73.7 74.6	Lean Press <sup>a</sup>	6.45 7.9 8.20 8.45	0 15 30 45
1.82 1.82 1.82		650 650 650	213 214 213	1.028 1.024 1.030	74.8 75.0 65.6		8.60 8.75 6.45	90
4 110 43	-Gutter and	d one per		r blade	at 7.5-in.	position	n; spool I	I
1.76 1.76 1.76 1.76 1.76 1.76 1.76 1.76	1.0 .67 .67 .58 .58 .53 .55 .57	651 654 656 660 664 676 653 648 643 650 664 649 657 649 650 652 647	207 208 208 209 211 215 207 206 204 206 233 227 220 219 212 204 197	1.064 .996 .933 .868 .807 .746 1.064 1.131 1.198 1.264 .882 1.180 .938 1.108 1.038 .996 1.100	73.3 76.5 78.2 78.7 78.3 72.3 67.8 62.0	Lean Rich Lean Rich Lean Rich Pressa Pressa		
V.	-Gutter and	d one per	rpendicula	r blade	at 11.5-in.	positio	on; spool	II
1.78 1.76 1.76 1.76 1.77	1.0	660 651 654 658 661	211 207 208 210 211	0.861 1.064 .996 .930 .864	76.3 71.4 74.2 75.9 76.7		6.9 8.25 7.85 7.4 6.85	eeri Heri

<sup>&</sup>lt;sup>a</sup>Minimum pressure.

TABLE I. - Continued. SUMMARY OF PERFORMANCE DATA

	atm	Inlet mixture temper- ature, OR	Inlet velocity, ft/sec	alence	Combustor efficiency, percent	Blow-out	Static- pressure drop,
1.76 1.76 1.77 1.77 1.77	1.0	665 675 652 649 645 652	212 208 207 206 208	0.806 .748 1.058 1.125 1.191 1.257	76.4 71.4 67.3 62.7	Lean	6.35 8.25 8.60 8.7
					5-in. positi	ion; spo	
1.78 1.78 1.78 1.78 1.78	1.0	657 656 650 676 652	210 210 208 216 209	1.055 .990 1.122 .756 1.259	69.3 71.7 66.2	Lean Rich	8.25 7.85 8.70
V-Gu	tter and or	ne perper	ndicular b	lade at	24-in. posit	tion; s	pool II
1.80 1.80 1.80 1.80 1.80	1.0	656 660 652 651 679	213 214 212 211 220	1.040 .956 1.128 1.326 .768	65.6 68.2 62.6	Rich Lean	8.5 7.7 9.05
V	-Gutter an	d one par	rallel bla	de at 1	-in. positio	n; spoo	1 I
1.295 1.295 1.290 .950	0.667 .667 .667 .500	657 657 636 648 639	230 230 222 222 219	0.862 .856 1.286 .974 1.167		Lean Lean Rich Lean Rich	
.945 .940 .935 .940 1.550	.500 .500 .500 .48 .833	640 644 656 653 670	218 218 221 230 225	1.150 1.161 .932 .975 .788		Rich Rich Lean Press <sup>a</sup> Lean	
1.56 1.810 1.820 1.330 1.310 1.310	.833 1.00 1.00 .667 .667	644 669 640 657 657 638	218 218 210 236 233 226	1.324 .780 1.358 .878 .884 1.252		Rich Lean Rich Lean Lean Rich	

<sup>&</sup>lt;sup>a</sup>Minimum pressure.

TABLE I. - Concluded. SUMMARY OF PERFORMANCE DATA

Air flow, lb/sec	Inlet static pressure, atm	Inlet mixture temper- ature, R	Inlet velocity, ft/sec	1 -	Combustor efficiency, percent	Blow- out	Static- pressure drop,
V-0	Sutter and	one para	allel blade	at 2.5	-in. position	on; spoo	ol I
1.315 1.320 .960 .950 .895	0.667 .667 .500 .500	654 635 647 635 640	233 227 224 218 223	0.880 1.272 .933 1.180 1.062		Lean Rich Lean Rich Press.	
1.555 1.590 1.820 1.835		661 635 662 632	222 218 217 209	.798 1.336 .736 1.338		Lean Rich Lean Rich	
V-0	Gutter and	one par	allel blade	e at 5.5	5-in. positi	on; spo	ol I
1.625 1.630 1.855 1.860 1.315	1.0	650 624 649 618 641	229 220 217 207 228	0.777 1.317 .746 1.352 .830		Lean Rich Lean Rich Lean	
1.290 .955 .970	.50	618 637 624	216 219 218	1.288 .898 1.178		Rich Lean Rich	
V-Gu pa	tter and orallel bla	ne perpe des at 2	ndicular b .5-, 4-, a	lade at nd 5.5-	l-in. position	ion and s; spoo	three
1.80 1.80 1.80 1.80	1.0	647 651 655 659 658	210 212 213 214 214	0.976 .909 .849 .789	75.2 76.9 76.9 74.9	Lean	8.7 8.05 7.25 6.4
1.80 1.80 1.80 1.80	.833	648 645 641 647 648	210 209 208 210 205	1.039 1.108 1.170 1.222 1.203	75.0 70.9 66.8	Rich Rich	9.25 9.55 9.55
1.47 1.175 1.175 1.175		667 650 662 660	212 206 210 229	.807 1.14 .900 .925		Lean Rich Lean Press <sup>a</sup>	

aMinimum pressure.

TABLE II. - PRESSURE DROP DATA ON CONFIGURATION VII OF REFERENCE 1

Equiv- alence ratio	Pressure drop,  ^p, in. Hg	Temper- ature ratio across burner	Combustor efficiency, percent
0.771 .819 .860 .903 .944	10.6 11.2 12.1 12.7 13.5	4.90 5.21 5.31 5.52 5.62	79.7 82.2 80.8 82.0 81.2
.988 1.032 .771 .73 .765	14.0 14.5 10.3 10.0 10.7	5.72 5.76 5.10 4.77 5.09	79.1 76.7 81.4 80.8 85.4
.724 .801 .850 .891 .932 .974	10.0 11.6 12.4 13.4 14.2 15.0	4.83 5.31 5.50 5.67 5.78 5.88 5.95	83.8 86.4 86.5 86.6 85.3 84.3

TABLE III. - PERFORMANCE DATA WITH PILOT HEAT VARIATION

Air flow, lb/sec	Inlet static pressure, atm	Inlet mixture temper- ature, OR	Inlet velocity, ft/sec	Equiv- alence ratio	Blow- out <sup>a</sup>	Pilot heat, percent				
	V-Gutter, no blade; spool I									
1.815	1.0	652 627 653 653 653	214 205 214 214 214	0.831 1.352 .814 .814 .768	Lean Rich Lean Lean Lean	0 0 0 0				
1.819 1.188 1.188	.67	653 623 623 646 646	214 204 204 208 208	.782 1.395 1.404 .898	Lean Rich Rich Lean Lean	.7 .7 .7 0				
1.180 1.180	.50	629 651 627 641 640	201 208 200 203 202	1.288 .830 1.346 .984 1.012	Rich Lean Rich Lean Lean	0 .7 .7 0				
.875 1.800	1.0	631 686 661 690 657	199 223 215 224 213	1.185 .813 1.341 .741 1.414	Rich Lean Rich Lean Rich	0 0 0 .7 .7				
.924	.50	668 668 657 670 650	223 222 219 223 217	1.014 1.024 1.146 .879 1.262	Lean Lean Rich Lean Rich	0 0 0 .7 .7				
.925	.30	658 653 652	220 218 363	1.082 1.122 1.080	Pressa Pressa (b)	0 0 .7				

<sup>&</sup>lt;sup>a</sup>With pilot, limits are smooth-burning limits, not actual blow-out; nonpiloted points are actual blow-outs. "Press." is minimum pressure.

bStill burning; choked condition with exhaust nozzle wide open.

TABLE III. - Concluded. PERFORMANCE DATA WITH PILOT HEAT VARIATION

	Air flow, lb/sec	Inlet static pressure, atm	Inlet mixture temper- ature, OR	Inlet velocity, ft/sec	Equiv- alence ratio	Blow- out <sup>a</sup>	Pilot heat, percent
	V-Gutter	, l perpe	ndicular	blade at	5.5-in.	positio	on; spool I
	1.86 1.87 1.87 1.83 1.83	1.0	656 637 658 669 646	220 214 222 221 213	0.862 1.252 .819 .804 1.296	Lean Rich Lean Lean Rich	0 0.7 .7
	1.41 1.40 1.38 1.41 1.41	.80	674 657 684 665 688	214 207 212 211 219	.860 1.218 .784 1.286 .816	Lean Rich Lean Rich Lean	0 0 .7 .7
	1.41 1.34 1.33	.75	689 663 685 680 667	219 214 219 218 213	.801 1.266 .820 .912 1.184	Lean Rich Lean Lean Rich	.7 .7 .7 0
	1.18	.57 .67	671 679 664	281 217 210	1.040 .855 1.182	(b) Lean Rich	.7 .7 .7
-		V-Gu	tter alor	ne, no blad	de; spoc	ol I	
	1.86 1.86 1.36 1.36 .90 .90	1.0 1.0 .77 .77 .50 .50	682 645 679 645 665 641 653	228 216 217 206 216 208 379	0.674 1.444 .699 1.394 .814 1.310 1.056	Lean Rich Lean Rich Lean Rich (b)	1.0 1.0 1.0 1.0 1.0 1.0

<sup>&</sup>lt;sup>a</sup>With pilot, limits are smooth-burning limits, not actual blow-out; nonpiloted points are actual blow-outs.

"Press." is minimum pressure.

bStill burning; choked condition with exhaust nozzle wide open.

NE 19

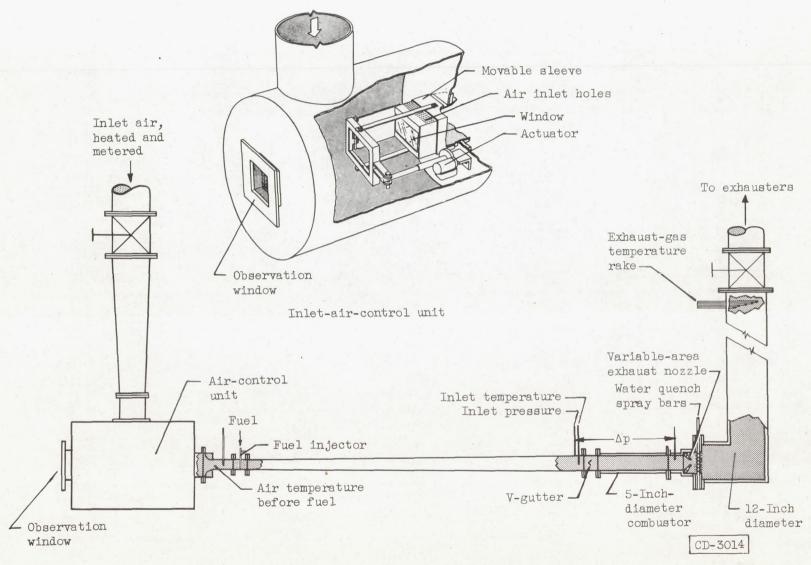
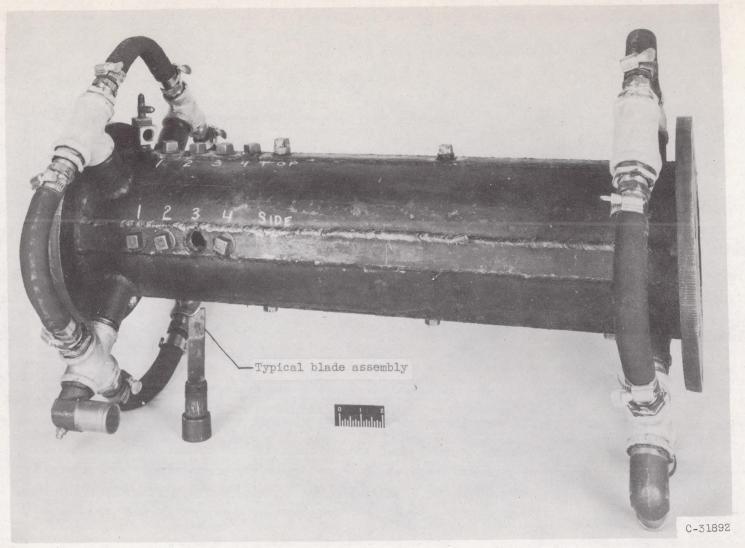
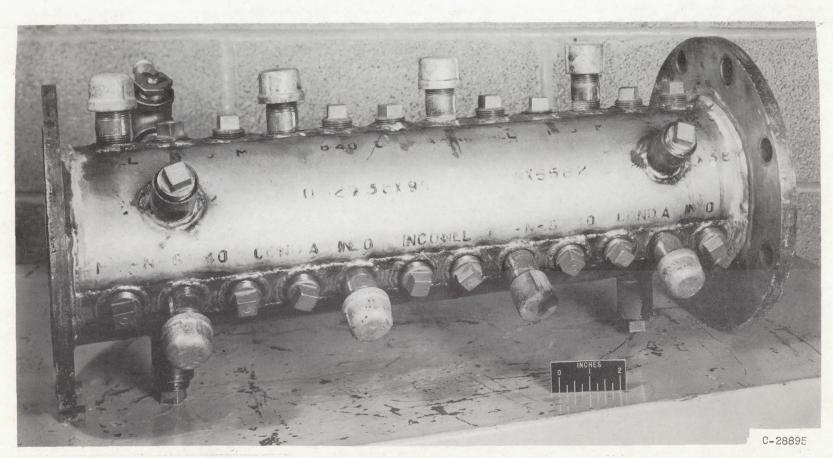


Figure 1. - Schematic illustration of 5-inch-diameter ram-jet combustor setup.



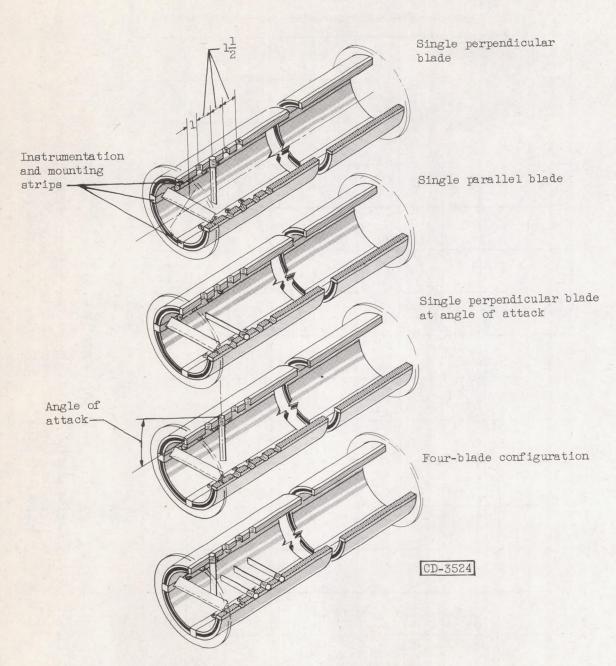
(a) Burner spool I.

Figure 2. - Details of burner configurations investigated.



(b) Burner spool II.

Figure 2. - Continued. Details of burner configurations investigated.



(c) Blade arrangements (dimensions in inches).

Figure 2. - Concluded. Details of burner configurations investigated.

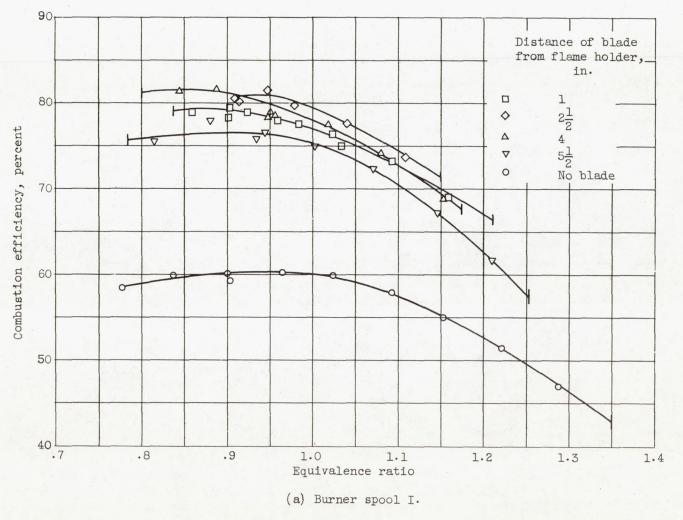


Figure 3. - Combustion efficiency of V-gutter alone and in combination with a single blade perpendicular to gutter at several axial locations. Inlet static pressure, 1 atmosphere; inlet mixture temperature, 660°R; inlet velocity, 220 feet per second.

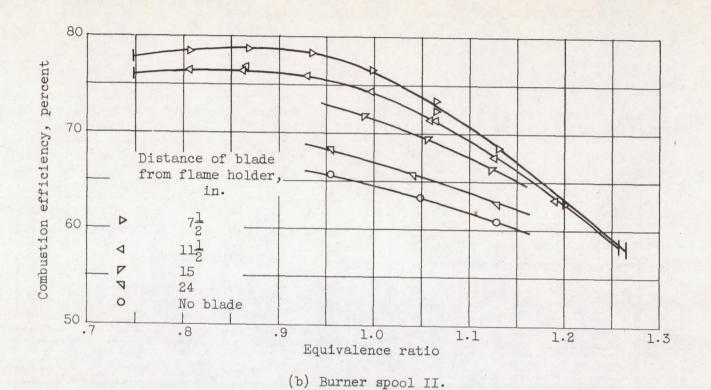


Figure 3. - Concluded. Combustion efficiency of V-gutter alone and in combination with a single blade perpendicular to gutter at several axial locations. Inlet static pressure, 1 atmosphere; inlet mixture temperature, 660° R; inlet velocity, 220 feet per second.



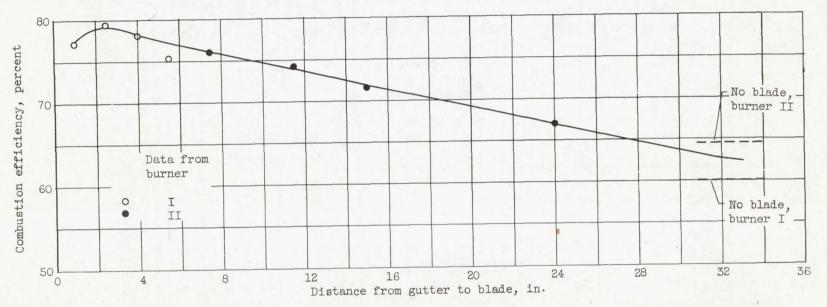


Figure 4. - Effect of axial position of single blade perpendicular to V-gutter flame holder on combustion efficiency of 5-inch-diameter ram-jet combustor. Equivalence ratio, 1.0; inlet pressure, 1 atmosphere; inlet temperature, 660° R; inlet velocity, 220 feet per second.

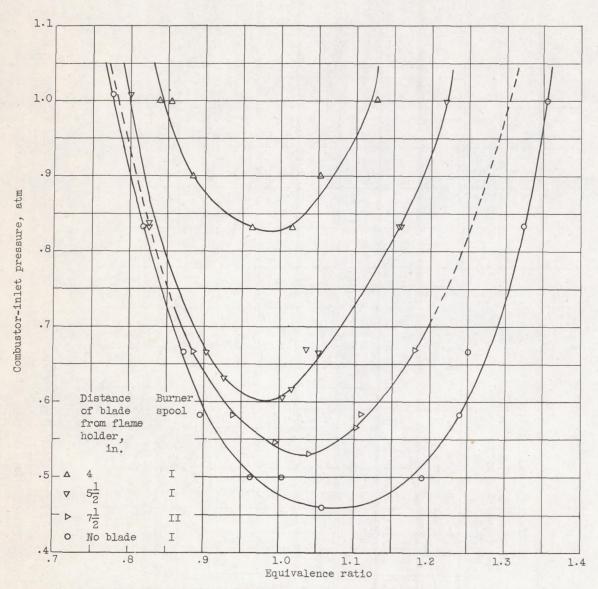


Figure 5. - Effect of axial position of single blade perpendicular to V-gutter flame holder on stability limit of 5-inch-diameter ram-jet combustor. Inlet temperature, 660° R; inlet velocity, 220 feet per second.



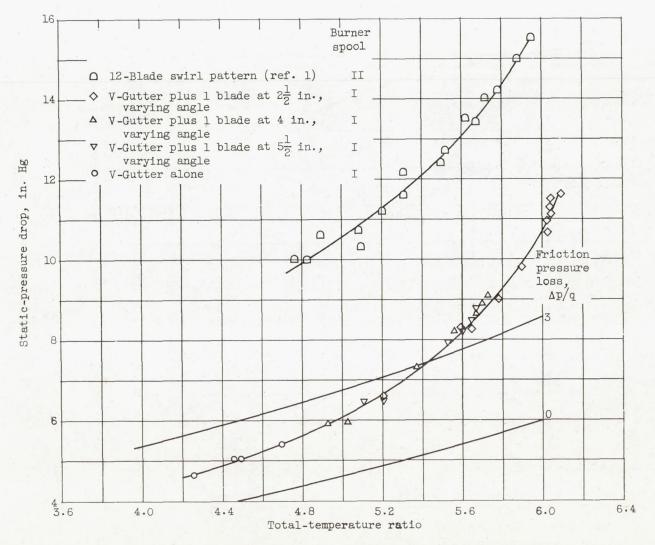


Figure 6. - Effect of total-temperature ratio on over-all static-pressure drop of burner for single perpendicular blade and multiple-blade configuration compared with theoretical pressure drop for heat addition alone in constant-area duct.

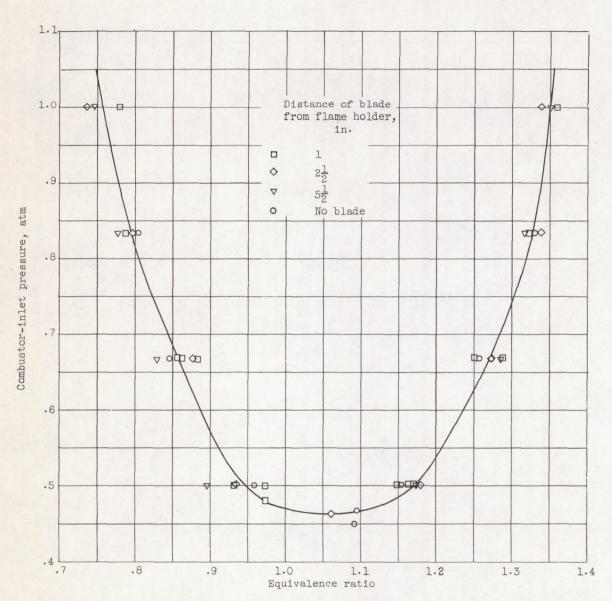
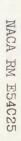


Figure 7. - Effect of axial position of single blade parallel to V-gutter flame holder on stability limit of 5-inch-diameter ram-jet combustor. Inlet temperature, 660° R; inlet velocity, 220 feet per second; burner spool I.



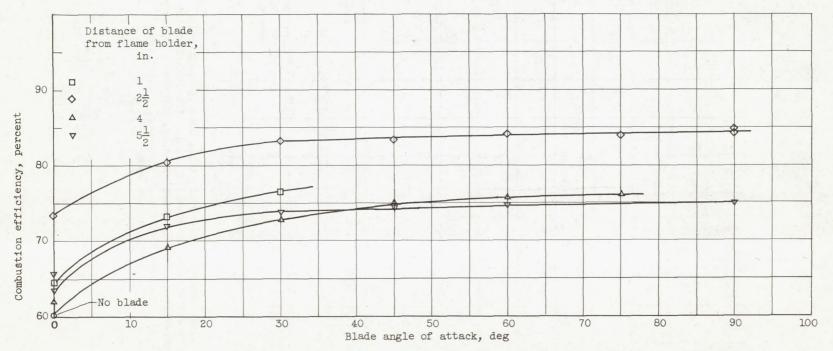


Figure 8. - Effect of blade angle of attack of single blade perpendicular to flame holder on combustion efficiency of 5-inch-diameter ram-jet combustor. Inlet static pressure, 1 atmosphere; inlet temperature, 560° R; inlet velocity, 220 feet per second; equivalence ratio, approximately 1.03; burner spool I.

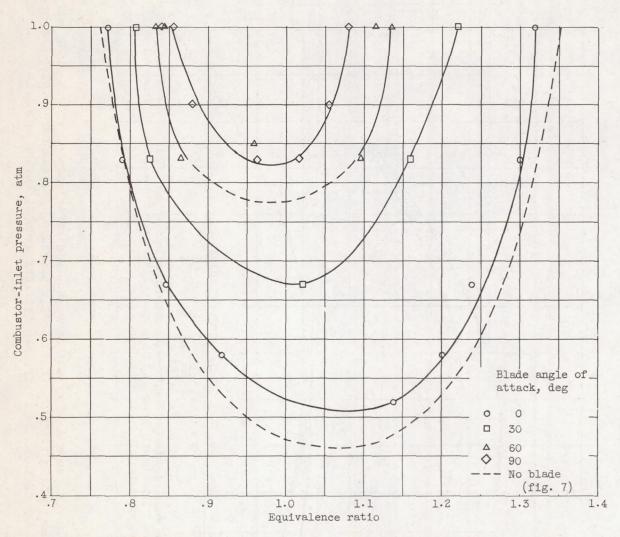


Figure 9. - Effect of blade angle of attack of single blade perpendicular to V-gutter flame holder, 4 inches downstream, on stability limit of 5-inch-diameter ram-jet combustor. Inlet temperature, 660° R; inlet velocity, 220 feet per second; burner spool I.



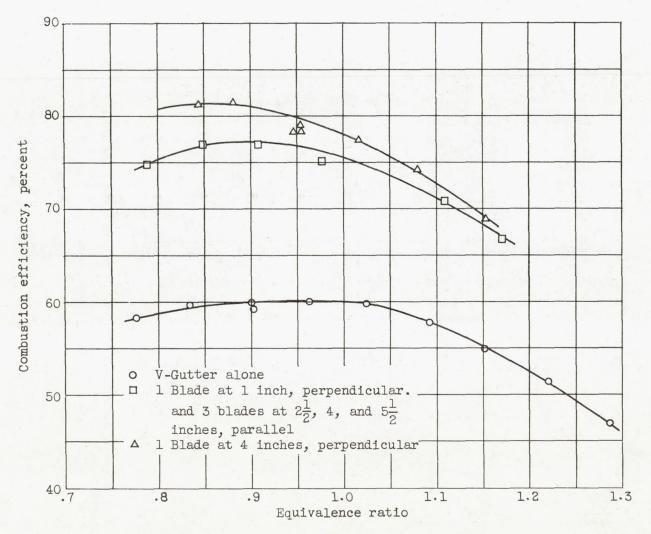


Figure 10. - Comparison of effect on combustion efficiency of single-blade and four-blade configuration. Inlet static pressure, 1 atmosphere; inlet temperature, 660° R; inlet velocity, 220 feet per second; burner spool I.

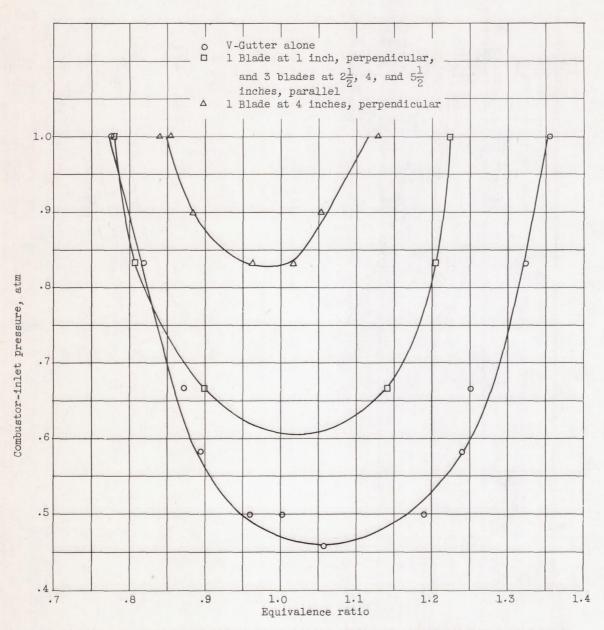


Figure 11. - Comparison of effect on stability limits of single-blade and four-blade configuration. Inlet temperature, 660° R; inlet velocity, 220 feet per second; burner spool I.

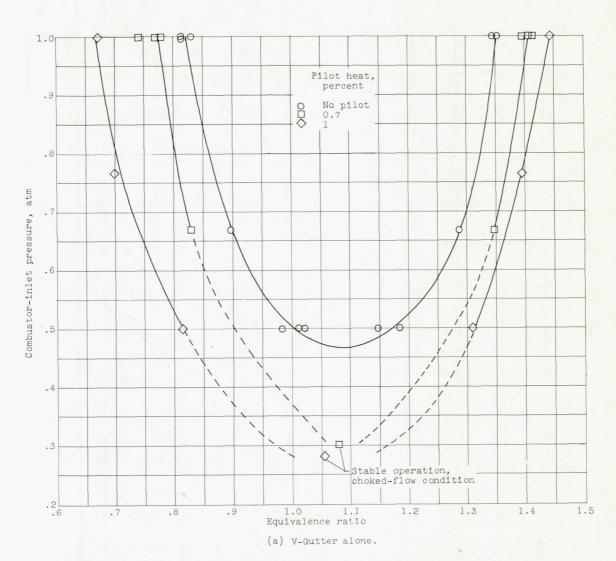
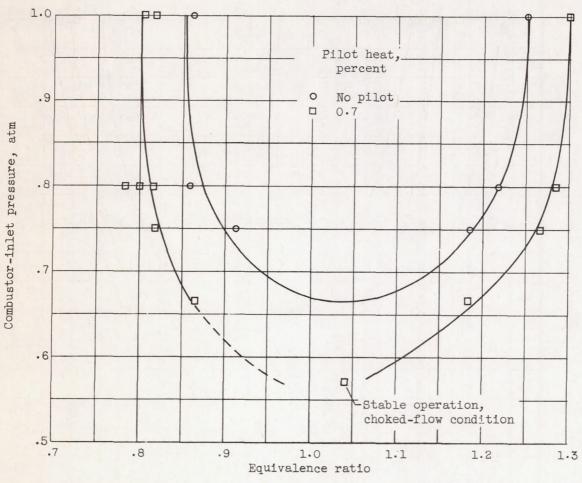


Figure 12. - Effect of pilot heat on stability limits of 5-inch-diameter ram-jet combustor. Inlet temperature, 660° R; inlet velocity, 220 feet per second; burner spool I. Pilot heat is expressed as percentage of net heating value of fuel at stoichiometric fuel-flow rate.



(b) V-Gutter plus one perpendicular blade at  $5\frac{1}{2}$ -inch position.

Figure 12. - Concluded. Effect of pilot heat on stability limits of 5-inch-diameter ram-jet combustor. Inlet temperature, 660° R; inlet velocity, 220 feet per second; burner spool I. Pilot heat is expressed as percentage of net heating value of fuel at stoichiomettic fuel-flow rate.